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"Natural thermoluminescence of Antarctic meteorites and related studies"

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Research Objectives

The natural thermoluminescence (TL) laboratory's primary purpose is to provide data on newly recovered Antarctic meteorites that can be included in discovery announcements and to investigate the scientific implications of the data. Natural TL levels of meteorites are indicators of recent thermal history and terrestrial history, and the data can be used to study the orbital/radiation history of groups of meteorites (e.g., H chondrites) or to study the processes leading to the concentration of meteorites at certain sites in Antarctica. An important application of these data is the identification of fragments, or "pairs", of meteorites produced during atmospheric passage or during terrestrial weathering. Thermoluminescence data are particularily useful for pairing within the most common meteorite classes, which typically exhibit very limited petrographic and chemical diversity. Although not originially part of the laboratory's objectives, TL data are also useful in the identification and classification of petrographically or mineralogically unusual meteorites, including unequilibrated ordinary chondrites and some basaltic achondrites.

In support of its primary mission, the laboratory also engages in TL studies of modern falls, finds from hot deserts, and terrestrial analogs and conducts detailed studies of the TL properties of certain classes of meteorites. These studies include the measurement of TL profiles in meteorites, the determination of TL levels of finds from the Sahara and the Nullarbor region of Australia, and comparison of TL data to other indicators of irradiation or terrestrial history, such as cosmogenic noble gas and radionuclide abundances.

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Research Progress - 1997

Our current work can be divided into five subcategories, (a) TL survey of Antarctic meteorites, (b) pairing and field relations of Antarctic meteorites, (c) characterization of TL systematics of meteorites, (d) comparison of natural TL and other terrestrial age indicators for Antarctic meteorites, and for meteorites from hot deserts, and (e) characterization of the TL properties of fusion crust of meteorites. Progress was made in each of these subcategories in this reporting period.

The natural TL survey had another productive year. Procedures developed over the last decade in conjunction with the curatorial facility at Johnson Space Center continued to result in the smooth transfer of samples for TL analysis during initial sampling of new Antarctic meteorites. We published natural TL data for 35 Antarctic meteorites (Attachments 1 and 2) with 33 currently in processing. Summary statistics for the project since inception are given in Table 1. The relatively small number of data published in this reporting period reflects a lull in the sample stream, the result of a period during which Johnson Space Center was engaged in clearing a backlog of very small meteorite samples, too small for TL analysis.

We have joined the initial publication of the natural TL data with an examination of possible pairings and notes on possible unusual petrographic features, such as high degrees of shock processing (Attachments 1 and 2). We are presently up-to-date with the publication of detailed analyses of our TL data for Antarctic meteorites from various icefields, having published summaries for the collections from the Allan Hills (ALH), Lewis Cliff (LEW), and Elephant Moraine (EET) (Benoit *et al.*, 1992, 1993, 1994).

In the previous year the natural thermoluminescence laboratory reached a number of important milestones in projects designed to support the utility of the data for Antarctic meteorites. We published a paper summarizing a significant portion of our natural TL data for modern falls, including data for 118 equilibrated ordinary chondrites (Attachment 5). As we suggested previously (Benoit *et al.*, 1991) natural TL data for modern falls should reflect their thermal history in space, and for most meteorites this should relate to their closest approach to the Sun (i.e., perihelion), the primary source of heat for meteoroid bodies.

Examining our database for equilibrated ordinary chondrites among the modern falls and applying equations describing TL equilibrium and the thermal profile of the inner solar system, we find that most meteorites apparently had orbits with perihelion between 0.85 to 1.0 AU prior to reaching Earth, with about 15% of ordinary chondrites having apparently had orbits with perihelia <0.85. As we have noted elsewhere, a very small proportion of meteorites have very high TL levels that must reflect disequilibrium conditions, reflecting very rapid orbital evolution from perihelia >1.1 AU to Earth (Benoit and Sears, 1993). The orbital distribution of most meteorites agrees well with estimates derived from indirect indicators, including orbits of fireballs, and the more limited database of estimates from observed falls. In addition, the TL data confirmed a key observation of meteoritics, namely that the orbital distribution of H and LL chondrites that fall in local morning (AM) differs from that in PM, a difference that has long been interpreted as indicating that most meteorites have orbits near 1.0 AU. Our data also suggested that a small proportion of H chondrites came from very similar orbits, and thus might have come from a debris "stream", a controversial idea suggested from time-of-fall data and volatile element chemistry (Dodd *et al.*, 1993; Schultz and Weber, 1996).

We also completed a detailed analysis of our TL data for lunar meteorites, all of our samples being from Antarctica (Attachment 4). In this study, in addition to reviewing induced TL data, we present a detailed analysis of the natural TL of lunar meteorites, including a discussion of the influence of terrestrial history and anomalous fading. A major conclusion of this study is that the natural TL of lunar meteorites largely reflects their exposure to cosmic ray radiation during their transit to Earth. We find that lunar meteorites generallly have short transit times, typically only a few thousand to tens of thousands of years, in contrast to most meteorites, which have cosmic ray exposure ages of millions of years (*e.g.*, Crabb and Schultz, 1981; Graf and Marti, 1994). In fact, the transit times of lunar meteorites are too short for accurate determination from cosmogenic noble gas abundances, so natural TL may provide the best estimate of transit times form these meteorites. The very short transit time for lunar meteorites is in accord with recent orbital calculations (Gladman *et al.*, 1996).

We also published the results of our studies of TL profiles of various large meteorites, and of a terrestrial meteorite analog (Attachment 3). The results of this work indicate that natural TL profiles in modern falls tend to be fairly flat, and thus that depth effects are fairly minor in typical meteoroid bodies. This result is not totally unexpected, since, unlike cosmogenic nuclides, TL reflects energy-deposited during passage of cosmic rays rather than specific nuclear reactions. Thus, both the primary and the secondary particles can contribute to TL production. Natural TL profiles in meteorite finds also appear to be fairly flat, although we did find one exception, ALH 78084. In this large Antarctic meteorite, a strong TL profile appears to be related to the find position of the meteorite on the ice and we suggest that this reflects a long-term thermal-profile between the warmed upper surface and the bottom surface on the ice.

We completed our examination of the TL of fusion crust of Antarctic meteorites (Attachment 6). Our original goal was to use the natural TL of fusion crust to produce an estimate of surface exposure age, following conventional TL dating procedures (Miono *et al.*, 1995). However, we found that natural TL levels were apparently at an equilibrium level in most Antarctic meteorites. We suggest that this is because the dark surface of meteorites can reach temperatures on the order of 10 °C by solar heating, and thus the equilibrium natural TL level is fairly low. As a result, TL equilibrium is reached within 150,000 years on the surface of the Earth. However, the TL of fusion crust potentially offers a better method for the measurement of terrestrial ages in the range of 40,000 to 200,000 years, a range in which ^{14}C and ^{36}Cl bear large uncertainties.

Table 1. Numbers of Antarctic meteorites for which natural thermoluminescence data have been obtained, divided by ice field and issue of publication in the Antarctic Newsletter or Meteoritical Bulletin. Most of these data are summarized in a complete compilation of Antarctic meteorites in Meteoritical Bulletin No. 76 (1994, Meteoritics 29, 100-143).

Field	11 (1)	11 (2)	12 (1)	12 (2)*	13 (1,2) +	13 (3)	14 (1)	14 (2)	15 (1)	15 (2)	16 (1)	16 (2)	17 (1)	17 (3)	18 (1)	18 (2)	19 (1)	19 (2)	20 (1)	20 (2)	Bul. 71	Met. Bul. 72
	1988	---	1989	---	1990	---	1991	---	1992	---	1993	---	1994	---	1995	---	1996		1997		1991	1992
ALH	82	7	1	1	26	6	6	8	1				9		2		11				40	10
BEC														1								
BOW	1																					
DOM	9							1														
EET		3		65	61		4		7	8	75		1	19	4							
GEO	2																					
GRA																				10		
GRO	14							1											3	11		
HOW					1	1																
LAP												1										
LEW	87	95	71	32	5	12		9	1								2					
LON																	3	7				
MAC				21	3	44																
MBR						1																
MET					3																	
MIL								1														
PAT												5	2									
PCA							1					38	21	3								
PRE																				1		
QUE		1		2					4	60	2				3	39	27	41	8			
RKP		4	2		2		1							2	2	2						
TIL												9										
WIS										4		10	2									
WSG																				1		
Totals :	195	110	74	121	101	64	12	20	13	72	77	63	35	25	11	41	43	48	11	24	40	10

Total published to date:	1210
Total measured:	1215
Samples in preparation:	28
Total Received:	1243

*Volume 12(2) was a special announcement for MAC88104,5 which included preliminary natural TL data.
+Volume 13(1) was a biennial index issue, which included a complete listing of natural TL data available, including about 100 unclassified samples.

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Attachments

Attachment 1. P. Benoit and D. Sears (1997) Natural thermolumescence data for Antarctic meteorites. *Antarctic Meteorite Newsletter*, **20(1),** 12.

Attachment 2. P. Benoit and D. Sears (1997) Natural thermoluminescence data for Antarctic meteorites. *Antarctic Meteorite Newsletter*, **20(2),** 13.

Attachment 3. P. Benoit and Y. Chen (1996) Galactic cosmic-ray-produced thermoluminescence profiles in meteorites, lunar samples, and a terrestrial analog. *Rad. Meas.* **26**, 281-289.

Attachment 4. P.H. Benoit, D.W.G. Sears and S.J.K. Symes (1996) The thermal and radiation exposure history of lunar meteorites. *Meteorit. Planet. Sci.* **31**, 869-875.

Attachment 5. P.H. Benoit and D.W.G. Sears (1997) The orbits of meteorites from natural thermoluminescence. *Icarus* **125**, 281-287.

Attachment 6. Akridge J.M.C., Benoit P.H., and Sears D.W.G. (1997) Fusion crust and the measurement of surface ages of Antarctic ordinary chondrites. *Lunar Planet. Sci.* 28, 15-16.

Attachment 7. Benoit P.H. and Sears D.W.G. (1997) Meteorite infall and transport in Antarctica: An analysis of icefields as accumulation surfaces. *Lunar Planet. Sci.* 28, 93-94.

Attachment 8. Benoit P.H. and Sears D.W.G. (1997) The cooling history and structure of the ordinary chondrite parent bodies. *Meteorit. Planet. Sci.* 32, A12.

Attachment 9. Benoit P.H., Akridge J.M.C., Sears D.W.G., Pillinger C.T. and Bland P.A. (1997) The weathering of Antarctic meteorites: Climatic controls on weathering rates and implications for meteorite acccumulations. *Lunar Planet. Sci.* 28, 95-96.

Table 4: Natural Thermoluminescence (NTL) Data for Antarctic Meteorites

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The measurement and data reduction methods were described by Hasan et al. (1987, Proc. 17th LPSC E703-E709); 1989, LPSC XX, 383-384). For meteorites whose TL lies between 5 and 100 krad the natural TL is related primarily to terrestrial history. Samples with NTL <5 krad have TL below that which can reasonably be ascribed to long terrestrial ages. Such meteorites have had their TL lowered by heating within the last million years or so by close solar passage, shock heating, or atmospheric entry, exacerbated, in the case of certain achondrite classes by "anomalous fading."

Sample	Class	NTL [krad at 250 deg. C]
QUE94204	E7	22 +- 5
GRO95535	HOW	11 +- 1
QUE94500	H5	36.0 +- 0.3
GRO95544	L3	<1
GRO95545	L3	<1
QUE94473	L5	16.0 +- 0.1
QUE94477	L5	1.9 +- 0.2
QUE94714	L5	64.8 +- 0.1
QUE94716	L5	4.2 +- 0.2
QUE94623	L6	4.4 +- 0.1
QUE94719	L6	21.4 +- 0.1

The quoted uncertainties are the standard deviations shown by replicate measurements on a single aliquot.

COMMENTS: The following comments are based on natural TL data, TL sensitivity, the shape of the induced glow curve, classifications, and JSC and Arkansas group sample descriptions.

GRO 95544 and GRO 95545 (L3) have very low induced TL sensitivities (0.003 and 0.006 relative to Dhajala H3.8, respectively) and are either type 3.1 or are highly shocked.

GRO 95535 (HOW) has low induced TL sensitivity (0.17+-0.02 relative to Dhajala H3.8) compared to most howardites, perhaps indicative that it is rich in diogenitic material (GCA 55, 3831-3844).

1. Pairings (Confirmations of Pairings):
   L3: GRO95544 and GRO95545 (AMN 19:2).

2. Pairings suggested by TL data:
   H5: QUE94500 with the QUE94217 group (AMN 19:2).
   L5: QUE94473 with the QUE90207 group (AMN 15:2, 19:2).
   L5: QUE94716 with the QUE 90205 group (AMN 15:2, 19:2).